A STUDY OF THE THEORY OF ELECTRIC CONDUCTION BETWEEN A CARBON BRUSH AND COPPER SLIP-RING

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BETWEEN A CARBON BRUSH AND COPPER SLIP-RING

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Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

United States Naval Postgraduate School
Monterey, California

1 9 5 2

This work is accepted as fulfilling
the thesis requirements for the degree of
Master of Science
in
Electrical Engineering
from the
United States Naval Postgraduate School.

Chairman

Department of Electrical Engineering

Approved:

Academic Dean

PREFACE

The object of this paper is to give an account of the theory of electric conduction between a carbon brush and a copper slip-ring. The physical characteristics of such a contact have been treated to a degree consistent with an understanding of the theory here described. This paper represents a compilation of one theory of conduction and serves to point out the scope that exists for further work in this field.

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INTRODUCTION

The subject of electric conduction across the interface between a copper slip-ring and a carbon brush is very extensive in its coverage. It includes a variety of incidental phenomena such as coherer action, the behavior of surface films, the effect of contact pressure in sliding action, and the effect of the relative motion between the contact members. The possibility of electronic conduction across the interface cannot be disregarded and must be dealt with.

The theory associated with the conduction of current across the interface is by no means complete. The theories presented in the literature agree in some phases of the phenomena and disagree in others. The investigators have not settled, as yet, on any theory that explains rigorously, in terms of the many variables, how current is conducted across the interface. This paper presents, in condensed form, a theory that is plausible in its logical approach to the phenomena.

PHYSICAL CHARACTERISTICS OF THE CONTACT

Before the theory of contact resistance in sliding contacts can be properly described, a word picture of the physical condition of such a contact must be presented. This picture must present, in the case of the carbon brush and the copper slip-ring, some mention of the effective area of contact as compared to the apparent area, the character of the surface films present on the copper and the brush face, and the effect of mechanical pressure on the contact. Once having treated the physical conditions somewhat thoroughly, it will then be possible to present the theories associated with conduction across the interface between a carbon brush and a copper slip-ring.

It is a very difficult matter to prepare surfaces which are really flat. Even on carefully polished surfaces, hills and valleys are present which are large compared with the size of a molecule. If two solids are placed in contact, the upper surface will be supported on the summits of the irregularities and the greater portion of the surface will be separated by a distance which is great compared with the molecular range of action. Although the techniques of grinding and polishing have advanced in the past few years, it is still a difficult matter to prepare surfaces of appreciable size which are flat to within 100 to 1000 Å. Our particular problem is not one of accurate grinding and polishing; however, it is one

of picturing the actual surface area in contact and the numbers of these hills and their shape. The smoothness will not be of primary importance and spacings greatly in excess of 1000 Å for most of the surface will be present. In addition to the lack of intimate contact over the entire area, surface films are present of certain thicknesses to further influence current transfer. Consequently, the familiar and well-known black film on copper, also called the current collector-film, will have to be investigated.

The phenomenon of conduction between two bodies in sliding contact is complicated by the relative motion between the bodies and the fact that the actual points on conduction are continually changing. Experimental investigations leave us with a mental picture of an interface consisting of a number of isolated small areas of contact (perhaps covered with a film -- perhaps not) whose locations continually change as the sliding motion proceeds. It is the present intent to now investigate this surface and thence to familiarize ourselves with the collector film.

THE EFFECTIVE AREA VS. APPARENT AREA OF CONTACT

We have already mentioned that even with carefully prepared surfaces the contact is usually established between a number of minute points; and, as will be seen later, the number and areas of these points increase with the mechanical pressure. Researches by Ragnar Holm (16) represent probably the first determination of the effective or real contact surfaces in a sliding contact formed by an electrographitic brush and copper ring. The number of small surfaces of varying size and shape comprising the interface was determined statistically by means of probes in the brush itself. The probe consisted of a cylinder of the brush material embedded in an insulated hole in the contact surface. The proportion of current flowing to the probe was registered and the average number of contact surfaces corresponding to the probe calculated from the duration of the periods in which the probe carried no current. The number of individual contact surfaces corresponding to the entire brush is then greater in the ratio of brush surface to probe surface. Resistance measurements then allowed determination of the magnitude of the actual contact surface. Holm concluded that the shape of the contacts has only small influence and can be taken into account by a suitable factor. It was found in the case of a well run-in brush with a total apparent contact surface of 2 cm^2

the number of actual contact surfaces ranged between six and eighteen with the contact pressure ranging from .5 to 1.1 Kg. The average diameter of the surfaces varied between 8 and 12×10^{-3} cm.. The aggregate effective or real area was then seen to be of the order of 10^{-3} cm^2, which, on the basis of a 2 cm^2 apparent area, is seen to be but one two-thousandth part of the total contact surface. On this basis, it is also seen that the pressure on the individual contact surfaces is approximately one ton per cm^2.

F. P. Bowden and D. Tabor (4) have carried out extensive experiments to determine the effective area of contact. The contact members were not in any case on record of carbon on copper but of various metals on metals. Notwithstanding, the results most emphatically point out that a very small fraction of the macroscopic area of the surfaces is in intimate contact.

Bowden and Tabor used steel surfaces finely ground and lapped flat in one series of experiments. One set had an apparent surface area of 21 cm^2. By measurements of the electrical resistance between the surfaces, and by the assumption that the asperities of the surface will be plastically deformed under load until the cross-section of the contact is sufficient to carry the load, the investigators were able to compile the following table for various loads:

TABLE I

LOAD-KG.	TOTAL AREA INTIMATE CONTACT-CM.^{2}	FRACTION OF AREA IN CONTACT - 21 CM^2 BASIS	RESISTANCE OHMS	NUMBER OF ASPERITIES IN CONTACT	AVERAGE RADIUS OF ASPERITY-CM
500	.05	$\frac{1}{400}$	$.9 \times 10^{-5}$	35	2.1×10^{-2}
100	.01	$\frac{1}{3{,}000}$	2.5×10^{-5}	22	1.2×10^{-2}
20	.002	$\frac{1}{10{,}000}$	9×10^{-5}	9	$.9 \times 10^{-2}$
5	.0005	$\frac{1}{40{,}000}$	25×10^{-5}	5	$.6 \times 10^{-2}$
2	.0002	$\frac{1}{100{,}000}$	50×10^{-5}	3	$.5 \times 10^{-2}$

The above table represents stationary contacts. The question may now be asked regarding the change of the number of asperities and the intimate contact area under sliding conditions. There will be a change, and it is true that the area of contact between moving surfaces does not remain constant. However, the average value of the conductivity (resistance), and hence the intimate or effective area is not very different from that observed at stationary surfaces (5). Though the data does not present the exact picture, it serves to point out that the real area of contact between sliding surfaces is small. Further, it should be noted that the number of asperities is not very large even at the heaviest loads.

THE COLLECTOR-RING FILM AND THE BRUSH FACE

The values of effective area determined by electrical means must be viewed with reserve since the presence of a small amount of oxide will have an appreciable effect on the results. The major part of the contact resistance between a carbon brush and a copper slip ring may be attributed to the insulating effect of the collector-ring film (16). To substantiate this claim, experiments have been devised in which the surfaces of various materials have been subjected to progressively higher voltages until such a time as the puncture voltage was reached (8). Surfaces freshly prepared with abrasive materials showed no puncture voltage. Further, no puncture voltage was found in the case of a carbon brush material (carbon exhibits a gaseous oxide). However, in the case of copper collector-rings which had been running for several days with electrographitic brushes, the puncture voltage ranged between .1 and 3.0 volts. In every case, where oxide films were present, the films acted as an infinite resistance until the puncture voltage was reached. These experimental truths lead directly to an investigation of the problem at hand -- what is the average collector-ring film composed of? Is the collector-ring film exclusively one of cuprous oxide? This question is answered by C. Van Brunt and R. H. Savage (15). They credit Dr. V. P. Hessler with having

been the first investigator to successfully isolate collector-ring films. By microchemical means, a sheet of film weighing 3.2 milligrams was stripped from a slip-ring and subjected to complete quantitative analysis. An analysis of a typical film is as follows:

TABLE 2

	PERCENT BY WEIGHT	WEIGHT GM/CM2	AVERAGE THICKNESS Å
Cu_2O	65.8	1.27×10^{-5}	210
C	22.1	$.42 \times 10^{-5}$	330
RESIDUE	12.1	$.24 \times 10^{-5}$	–
SUM	100	1.93×10^{-5}	540

The figures given for average thickness are computed from the weight and average densities. Further, it is reported by William H. J. Vernon that a cuprous-oxide film of 210 Å would exhibit a color between orange and bluish-purple. According to Hessler, a pale orange tint was observed in many isolated fragments of the specimen, lending credence to the thickness of cuprous oxide reported. In several instances, the orange tint did not extend over the entire fragment but was sharply discontinuous, as

one would expect if it were due to a separate layer which could break away. It was subsequently found that this could be done without disturbing the carbon portion of the film. The two were separate strata, the lower being the cuprous oxide related to the copper slip-ring and the upper layer of carbon related to the brush.

Although cuprous oxide has been given great consideration by the investigators, cupric oxide seems to have been completely disregarded. Cuprous oxide formed in the presence of air is a semi-conductor. Cupric oxide is a good insulator. V. P. Hessler in his work on collector-ring films (8) accidentally spilled several drops of water on a copper ring he was investigating. After a little while, the moistened portion of the ring had become rather black in color. The black portion (cupric oxide) gave a puncture or breakdown voltage of 3.5 volts which was very much higher than the value for the reddish film (cuprous oxide) beside it. When studied with an oscillograph with the ring in motion, the current remained practically constant until the black spot came into contact. At that point, the current fell to zero and then built up to its previous value as the black spot passed by. I mention this fact only because it may in some cases of temperature and humidity be responsible for variations in contact drop. That is, there is a possibility that under special circumstances there are present three strata in collector-ring films; the cuprous oxide

film, the cupric oxide film, and the carbon film, in that order.

The character of the contact face of a carbon brush bears special interest in brush wear considerations. Although this paper is not primarily concerned with the wear problem, the brush face is here discussed so that a possible aid to conduction of current across the interface between an electrographitic brush and copper slip-ring may be mentioned. R. H. Savage (11), by use of the electron microscope, throws an interesting new light on the term "brush" as applied to the carbons used in electrical machinery. Wire bundles were called brushes in early electrical machinery development. After their replacement by carbon, the term "brush" was retained although the carbons are in the form of blocks. The blocks are regarded as rather brittle and inelastic solids, the faces of which make contact with rotating collectors through only a few spots. From electron micrographs, it is apparent that the face of the carbon is in reality a microscopic brush and that the contact must be made through an enormous number of very small elements, many of which are in the form of graphite fingers. Although the number of fingers in actual contact must be in the order of thousands, the actual intimate contact area is still much less than 1% of the apparent surface.

It has long been known that the friction of graphite is low even in the absence of lubricants, and it has generally been

considered that it is due to the lamellar structure of graphite. However, R. H. Savage (12) sheds new light on the phenomena of graphite lubrication and this is important in the theory of current transfer across an interface because of the presence of a monolayer of water vapor. Savage found, while investigating wear between a carbon brush and copper slip-ring that for graphite surfaces freed from contaminant films by heating in a vacuum, the wear was very high and the friction is higher. This suggested that contaminant films must play an important part in graphite lubrication. The addition of hydrogen or nitrogen to the system did not affect the heavy wear rate. However, if water vapor is admitted at low pressures, the friction is reduced to the usual low value and the wear is eliminated. Under normal conditions, this absorbed layer of water vapor is provided by atmospheric moisture. An example to substantiate this claim is provided in the high wear rate experienced by brushes in aircraft at high altitudes where the atmospheric moisture content is low. This suggests that water is acting as a lubricant between the stratum of graphite on the collector-film and the brush face.

It has been mentioned that the brush surface contained many graphite fingers which are projecting portions of the large and irregular graphite plates composing the brush. Prior to the use of the electron microscope, it was thought that the brush surface

consisted of graphite plates oriented with their hexagonal planes flat and parallel to the plane of motion. By use of the electron microscope (6), the surface is seen to possess a directional overlap of graphite plates, the direction of overlap being determined by the direction of motion. The graphite plates are inclined at various angles up to 90° in the extreme, the majority at an angle of less than 45° with the plane of motion.

We now have this picture of the interfacial films. The collector-ring film consists of two separate stratum, one of cuprous oxide adjacent to the copper of slip ring, and another of graphite adjacent to the cuprous oxide. Possibly there is still another film of cupric oxide between the two previously mentioned levels. The brush face consists of tilted graphite plates oriented up to 90° with plane of motion. Wear studies indicate that a monomolecular layer of water vapor, under ordinary conditions, is present between the graphite face of the brush and the graphite of the collector-ring film. This interfacial film is what constitutes the major portion of the contact resistance and across which the current must be transferred.

CONTACT PRESSURE

In Ragnar Holm's determination of the effective contact area in a sliding contact, mention was made that, on the basis of the brush pressure used and the effective area determined, the pressure present on an individual contact surface was approximately one ton per square centimeter. This represents a pressure which is closely allied to the hardness of the brush material which in this case was 1400 kilograms per square centimeter. So it would seem that the effective area of any contact is a function of the force holding the members together.

Bowden and Tabor (4) found that they achieved good results in the measurement of effective contact area by assuming that the load equaled the product of the effective area and yield pressure of the softer material. This formula assumes that the specimens are fairly highly worked. Considering the asperities in sliding contacts, it seems logical to assume that they are worked considerably by the sliding motion. With a given material, such as copper, it seems plausible to assume that on increasing the brush pressure, the copper yields sufficiently to carry the load. It is not known whether more asperities come into contact or whether the copper area previously in contact tends to grow by plastic deformation as pressure is applied. Logically it seems that both effects would come into play with the latter predominating.

In any case, with increasing brush pressures the contact resistance decreases, owing to the increasing number of contact points and their increasing areas coming into contact.

THE THEORY OF CONDUCTION

If two bodies are brought into contact under pressure, they will touch at several isolated points; and, if we assume that there is no surface film present, it can be said that under these conditions, there is actual contact between the two bodies. If the bodies are electrical conductors, it is then possible for current to pass from one body to the other. In its passage the current encounters resistance. This resistance is known as contact resistance and its value depends upon:

1. The kind of materials used for each contact member,
2. The condition of the contact surfaces -- smoothness,
3. The mechanical pressure acting upon the contacts.

The lines of current flow in the contact members are constricted at the isolated points of contact and hence their paths of flow are lengthened, thus increasing the resistance between the contacts. The total contact resistance consists virtually of three independent resistances; two of the constriction variety, and the other the resistance offered to the flow of current during its passage across the interface. It is this latter interfacial resistance which will be discussed. The flow of current in its passage across the interface encounters the collector-ring film, is further hindered by sliding action and by some means is able to negotiate the barrier.

One theory will be presented on how current conduction is achieved in the case of a carbon brush and a copper slip-ring. This theory is due to Ragnar Holm and is contained in his book Electric Contacts (10). A second theory will be presented in part. The investigator is P. F. Soper (14) and his paper is entitled Carbon-Brush Contact Phenomena in Electrical Machinery.

The theory presented by Holm involves in the main the phenomena called "coherer action". In arriving at a plausible explanation of current conduction, Holm noticed the similarity between the coherer effects in a stationary contact resistance-voltage curve and the resistance-voltage characteristics of a sliding contact. Knowing that the electric conductance through a sliding contact must be of the same kind as through a stationary contact if the velocity of sliding is not greater than the thermal velocity of electrons, he was able to apply stationary contact theory to sliding contact theory. In so doing, coherer action was theorized as being the main contributing phenomena in current conduction across an interface.

Coherer action in stationary contacts is illustrated in the following way. A metal contact (say copper) with a tarnish film (collector-film) is connected in series with a resistance and ammeter to a current source in such a way that it enables the voltage, beginning with small ~~volumes~~ values, to be gradually increased.

Beginning with small voltages, the collector-film is practically an insulator -- only a very slight current flows. But as soon as the so-called puncturing voltage is reached, the current suddenly rises because of an abrupt drop in the contact resistance. The described change is the coherer action.

Holm made measurements on a cuprous-oxide sample. The contact was formed by a copper rod carrying the film on a gold rod of the same shape and dimensions placed across the other. For the resulting curve see Figure I. Curve A+ refers to the copper rod as the anode and curve B- that of the copper rod as the cathode. Note that in each case a voltage maximum was reached at approximately 1.8 - 2.5 volts. This represents the puncturing voltage and the initiation of the coherer action. Now on trying to increase the current still further, there occurs an abrupt improvement of conductivity which has been called coherer action. This is illustrated by the dashed parts of the curves. As seen from the curves, coherer action resulted in lowering the contact resistance from 5×10^5 to 5700 ohms and the contact voltage to .4 volts. In taking these readings, a series resistance of 10^6 ohms was used. If a smaller value of resistance had been used in series, the contact resistance could have been lowered still more. But whatever the resistance measurements at the end of the coherer action, the contact voltage remains at .2 - .5 volts.

CONTACT RESISTANCE - CONTACT VOLTAGE CHARACTERISTICS

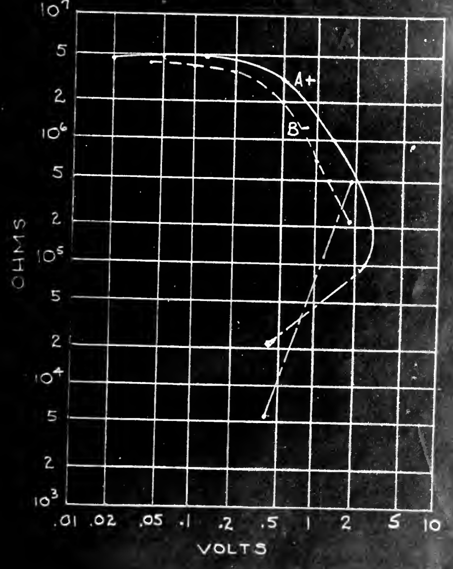

FIGURE 1

The fact that the contact voltage remained at .2 - .5 volts led to the conception of metallic bridges. The above range of voltage drop corresponds to the melting voltage of copper, which is .43 volts at 1083°C. A melting voltage is defined as the voltage corresponding to the melting temperature of a metal. On the assumption that the melting voltage together with the melting temperature is present at the isolated points of contact, it seems feasible that molten copper is available to form metallic bridges. The theory of coherer action begins with a puncturing or breakdown of the film producing a channel in it, which fills with molten metal, finally solidifying. As long as the bridge consists of molten metal, it grows, because the I^2R heat supplies new molten metal from the electrodes. The molten metal is drawn into the channel until the bridge is large enough to accommodate the current, and then it stops growing.

The phenomena associated with puncturing the film is somewhat sketchy. A plausible explanation is suggested. The puncturing or breakdown of the film occurs when the electrostatic field becomes so strong that an average free electron in a lattice can gain more energy from the field between collisions than it loses as a result of the collision. Progressively the electron is able to gather enough energy for ionizing after moving only a few free paths and electron avalanches result. This avalanche produces

high temperatures and somehow brings about a channel. Possibly the cuprous oxide is reduced to copper ions by the high temperature, thus forming the bridge. This is plausible. Holm reports that G. L. Pearson in his work on the formation of metal bridges employed electrodes of gold, steel and carbon, which he brought so near to each other that a contact gap of 2×10^{-6} to 70×10^{-6} cm was attained. When a mean electrostatic field of 10^7 volts per centimeter was set up, small conducting bridges were formed, consisting of the electrode material. Possibly the strong field gathered ions at the metal surface placing them where the lines of force were closest, thus building a bridge.

As already stated, sliding and stationary contacts between similar members with similar contact surfaces possess equal conductance. But in the sliding contact of a graphite brush on a copper ring complications arise because of the well-known black collector-film. When a brush is well run-in, the black film is very little damaged from sliding action. Therefore, there occur very few metal contact spots and the conduction is poor until higher voltages cause an alteration in the film. The alteration to the film will now be discussed. The discussion will be focused on curves showing the contact resistance plotted against the contact voltage (see Figure II). Figure II shows two sets of curves. Curves A- and B+ refer to the negative brush and the positive brush respectively, both

with a brush pressure of 150 grams. Curves a- and b+ refer to the negative brush and the positive brush, respectively, at a pressure of 1000 grams. All points of these curves are permanent states -- readings were taken for each point after a run of one hour.

Several facts can be derived from the curves:

1. The characteristics are too steep and the resistances are too high to be attributed solely to the resistivity of the brush and its dependence ~~of~~ on temperature.
2. Polarity differences are pronounced at small currents.
3. At large currents, the polarity effects disappear.
4. The static characteristics appear to be asymptotic to a value between .5 and 1.7 volts. This is the well-known contact voltage drop experienced in current collectors.

At this point, Holm observed a similarity between these curves and those of Figure I. However, the stationary curves had a definite puncturing voltage, whereas the sliding contacts appear to be experiencing puncturing throughout the steeply falling part of the curves.

If a slip-ring which has been kept still for a long time begins to rotate under a current-carrying brush, the collector-film

CONTACT RESISTANCE - CONTACT VOLTAGE

CHARACTERISTICS

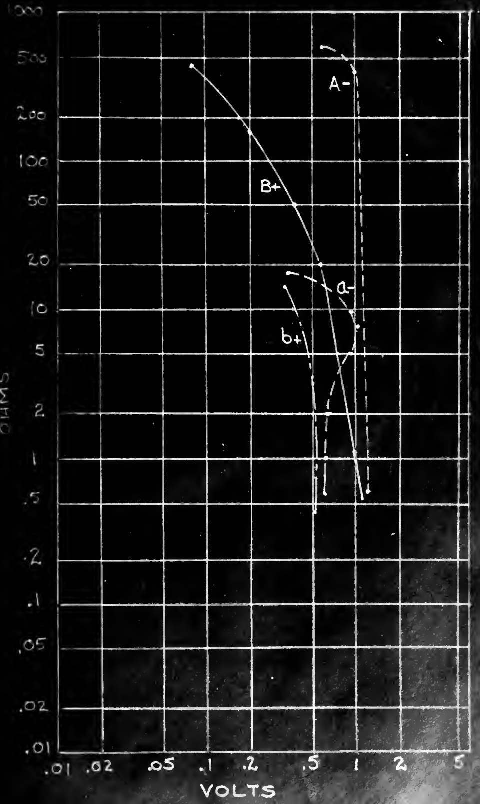

FIGURE 2

insulates at first. But the contact voltage may become sufficiently high to puncture the film, which thereby becomes studded with coherer bridges. It has been suggested that the metal bridges are formed in punctured holes and these bridges are just large enough to carry the current without melting, and that this condition is indicated by the contact voltage called the bridge voltage, which has about the same value as the asymptotes. This suggests the hypothesis that the asymptote voltage is a bridge voltage.

The question now arises regarding the melting voltage before mentioned in the case of the stationary contact. It seems reasonable that a higher melting voltage will be required to supply the molten metal for the bridges since in sliding contacts the contact spots are in actual contact only a short time. It is possible that the contact spots have sufficient time to cool between brushes to a temperature well below the melting temperature. However, the higher voltage is not necessary because friction supplies the missing heat and somewhat more.

Finally, we expect the bridge voltage in the brush contact to be about the same as the bridge voltage of stationary contacts, and this is the case.

The polarity effects noted in Figure II remain somewhat of a mystery. Holm attributes the effects in part to rectifier action. The rectifier action is a phenomena of the work functions of the

various constituents making up the contact -- the copper, the collector film, and the brush. R. F. Soper (14) believes that the polarity effect is due to the different nature of the emitting surfaces and the different work functions of the constituents. As a possible explanation of polarity differences in the voltage-resistance characteristics, the theory attributed to R. F. Soper will now be presented.

Soper used a generalized form of the Fowler-Nordheim equation to explain polarity effects on the basis of high-field emission. Prior to examining the equation, it is well to touch on the high-field emission theory. All conductors contain free electrons which possess a Fermi energy expressed in electron-volts. In order to extract these electrons from the conductor surface by thermionic methods, they must be given an additional energy called the thermionic work function. Now an electron just outside the metal surface will tend to be drawn back to the metal by surface forces. However, if an applied external field is of sufficient strength, the electron will tend to leave the surface even though the electron has not acquired a value of energy corresponding to the thermionic work function. The application of an external field produces two effects. First, it decreases the height of a so-called potential barrier, and second, it decreases the thickness of the barrier. The first effect allows electrons with energies less than the work

function to escape over the top of the barrier. Secondly, it allows electrons whose energies are less than the height of the barrier to penetrate the barrier on account of their wave properties. If the externally applied field is great enough, the electrons may percolate through the barrier, even though their energy is less than the Fermi level. Using Planck's hypothesis and various other wave mechanics formulas, the author was able to demonstrate that for electric field strengths in excess of 10^5 volts per centimeter appreciable energy in the form of electrons can be transferred across the surface of a conductor. This energy will be through the barrier and not over the barrier.

The Fowler-Nordheim equation for high-field emission gives the current density due to high-field emission in terms of the electric field intensity, the work function of the emitter, and the Fermi energy of the electron. The equation is as follows:

$$i = \frac{6.2 \times 10^{-6} \sqrt{\mu'}\, \mathcal{E}^2}{(\phi + \mu')\sqrt{\phi}}\, \epsilon^{-\left[\frac{6.8 \times 10^7 \phi^{3/2}}{\mathcal{E}}\right]}$$

Where, ϕ, work function of the emitter

μ', Fermi energy of the electron

$\mathcal{E}$, electric field intensity

i, current density

Putting the contact voltage drop equal to the product of the effective contact spacing and the electric field intensity, and

by further multiplying the current density by the emitting area, Soper arrived at a generalized Fowler-Nordheim equation:

$$I = \frac{k_1 A V^2}{X^2} \epsilon^{-k_2 X/V}$$

Where, I , current

k_1 & k_2 , constants calculated from values of ϕ and μ'

A , emitting area

X , effective contact spacing

V , contact voltage drop

By taking logarithms of both sides of the equation and then resorting to graphical analysis, the author was able to determine the values of the effective contact spacing and the emitting area. The effective spacing was approximately 10^{-8} cm and the effective area was of the order of 10^{-7} square cm. It is thus evident that the passage of the current through the contact must be confined, at any instant, to a few very minute points.

By assuming that the current transfers across an interface is due solely to high-field emission, as our author has done, it can be said that the contact drop is a function of the emitting area, the contact spacing, and to a lesser degree, the work function of the emitting surface. This narrows the number of variables for given contact materials to three. That is, the mechanical pressure,

the speed of sliding, the humidity, and the coefficient of friction only control the value ofthe contact drop insofar as they modify the values of contact spacing and emitting area.

The theory so far developed is applicable to reasonably clean unoxidized collector-ring surfaces. When the collector-ring film is present with its graphite stratum, a portion of the potential barrier is made less thick and therefore more energy is allowed to penetrate the barrier. However, a "film factor" is introduced into the generalized emission equation, which reduces the emission area and thence reduces the current transfer across the interface. Thus, the effect of a collector-film on a slip-ring is to reduce the current transferred by a given contact-drop by the film factor, all other conditions remaining unaltered.

Soper conducted two separate experiments to demonstrate how the contact voltage drop is effected by polarity. The first experiment treated the particular case of a carbon brush designated as H. M. 3 grade riding on a cast-iron slip-ring. Each polarity change was allowed to operate for twenty hours before the readings were taken. The resulting readings and calculations are as follows:

TABLE 3

EFFECT OF BRUSH POLARITY WITH A CAST-IRON RING

Operating Property	Negative Brush	Positive Brush
A, cm^2	1.67×10^{-9}	4.9×10^{-9}
X, cm.	7.69×10^{-9}	5.68×10^{-9}
V, volts	1.82	1.22
$\mathcal{E}$, volts/cm.	2.37×10^{8}	2.15×10^{8}

The results indicate that the effective contact spacing, X, is greater when the brush is negative, and explains why the contact drop is greater for the negative brush. This is due to the need for the field strength, $\mathcal{E}$, to be increased to such a value that the required emission is obtained from the smaller emission area, A.

A similar set of data was collected for a copper slip-ring and the results are as follows:

TABLE 4

EFFECT OF BRUSH POLARITY WITH A COPPER SLIP-RING

Operating Property	Negative Brush	Positive Brush
A, cm^2	$.486 \times 10^{-9}$	$.297 \times 10^{-9}$
X, cm.	2.78×10^{-9}	2.34×10^{-9}
V, volts	.52	.85
$\mathcal{E}$, volts/cm.	1.87×10^{8}	3.63×10^{8}

Note that in this case the greater contact voltage drop occurs under the positive brush. The results appearing in the two tables are perfectly general, no matter what materials are employed for either the brush or the ring. The values of emission area are inherent with different materials, owing to the different abilities of the constituents of a contact to plastically deform, to flow, and to work-harden.

Thus, it seems that this compilation explains in a plausible manner the phenomena occurring at the interface between a carbon brush and a copper slip-ring. However, explanations which depend on logic are sometimes fallacious. In the description, no mention has been made of the effect of the coefficient of heat transfer of the constituents of the contact. This effect might be of paramount importance. Further, Holm's rectifier effect to explain polarity may be the proper approach to the polarity problem. Notwithstanding, it is the opinion of the author that when, if ever, the phenomena are definitely attributed to known physical facts and these facts stand the tests of experiment without variation from one test to the other, then the above compilation will, to a great degree, enter into any future, more rigorous explanations.

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Thesis G453
Giorgis
A study of the theory of electric conduction between a carbon brush and copper slip-ring.